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Fleet Sizing for Offshore Supply Vessels with Stochastic Sailing and Service Times

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Abstract

In this paper we address a supply vessel planning problem arising in servicing oil and gas offshore installations. Supply vessels provide offshore installations with necessary supplies on periodic basis from offshore supply bases according to weekly sailing schedules. The execution of weekly schedules during the year is affected by weather conditions influencing on sailing time and service duration at installations. When the contracted vessel cannot complete a voyage before the start of its next planned voyage, a vessel from the spot market is hired to perform it. Deciding on the number of supply vessels hired to perform operations from a supply base for a year ahead has a strong economic effect on the total annual vessel costs. We present a discrete-event simulation model for evaluation of alternative fleet size configurations taking into consideration uncertainty in weather conditions and future spot vessel rates. The model is validated and tested on real data.

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Keywords: Discrete-event simulation; Fleet sizing problem; Periodic routing and scheduling; Oil and gas industry

1. Introduction

In offshore oil and gas logistics efficient planning of supply vessel operations is extremely important as ongoing activities at production platforms and mobile drilling rigs depend on timely supplies. Moreover, the decision on the size of the supply vessel fleet and its utilization has a strong economic effect as these vessels are rather expensive. In this paper we address a supply vessel planning problem arising in servicing oil and gas offshore installations on the Norwegian continental shelf.

Supply vessels provide offshore installations with necessary supplies on periodic basis from onshore supply bases according to weekly sailing schedules. A set of installations to be serviced from a supply base is predefined. A weekly sailing schedule determines a vessel fleet and a set of voyages for each vessel to sail from the supply base during the week. Each voyage represents a route with duration of several days, a given start day and a sequence of installations to visit. The problem of determining optimal supply vessel routes, taking into account limited deck capacities at

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offshore installations, is studied in [1,2]. The periodic supply vessel planning problem consisting of determining fleet composition and weekly vessel schedules is studied in [3,4,5,6]. In all these papers supply vessel planning problems are considered as deterministic. The planning of supply vessel schedules, robust to uncertainty in weather conditions, is studied in [7].

Oil and gas companies operating offshore usually do not own supply vessels, they are hired from shipowners and shipbroker companies. Vessels hired for a long term period (from one to three years) are referred as time-charter vessels. Time-charter rates play major role in determining the minimum required number of vessels in a weekly sailing schedule. A weekly sailing schedule is usually valid for a finite number of weeks before another schedule is developed due to changes in installations' activities and location. The number of time-charter vessels operating from a supply base dynamically varies during the year according to the changes in its weekly schedules. The execution of weekly schedules is affected by weather conditions. The duration of service operations at installations and sailing time increases when weather conditions deteriorate. In compliance with guidelines for safe offshore operations [8], supply vessels are not allowed to perform service at installations when wave height and wind speed exceed certain thresholds. Because of the bad weather, duration of a voyage scheduled for a vessel may be longer than planned, so that this vessel cannot return to the base in time to start its next planned voyage. In such cases, another time-charter vessel is used. The shortage of available time-charter vessels forces the company to hire a supply vessel from the spot market to perform the voyage. Insufficient number of time-charter vessels employed for a year may result in the frequent use of spot vessels. The optimal mix of time-charter and spot vessels to be used during a year will depend on future spot rates that may be significantly higher and volatile as opposed to time-charter rates.

This study is related to the annual supply vessel fleet-sizing, namely deciding on the number of time-charter supply vessels hired to perform supply operations from a single base for a year. The dependence of supply vessels' operations on weather conditions make the fleet sizing problem highly stochastic. Due to impossibility to describe and model the stochastic phenomena analytically, discrete-event simulation modeling is used as a methodology. In this paper we present a discrete-event simulation model that evaluates alternative fleet size configurations for an annual time horizon taking into consideration uncertainty in weather conditions and future spot rates. The discrete-event simulation model for the fleet sizing of anchor-handling tug supply vessels performing rig moves under stochastic weather conditions is studied in [9]. However, operations associated with rig moves have completely different nature compared to the periodic service of installations performed by supply vessels from an onshore base. Model in [9] simulates an annual sequence of rig moves, while in our simulation model a sequence of voyages, performed according to the annual set of weekly schedules, is simulated.

The remaining of this paper is structured as follows. Section 2 describes supply vessel voyage, provides an example of a weekly sailing schedule and explains the logic of the discrete-event simulation model of annual vessel schedule. In Section 3, we describe modeling of operations on voyage including weather-dependent sailing and service durations. Modeling of weather and spot vessel rates inputs, and general assumptions are explained in Section 4. Model validation and analysis of simulation output is given in Section 5. Conclusions are given in Section 6.

2. Simulation model of annual vessel schedule

In this section we describe supply vessel voyage and the sequence of operations performed along the voyage followed by an example of a weekly vessel schedule. Afterwards, the logic of simulation model is explained.

2.1. Supply vessel voyage

A vessel voyage can be represented as a set of activities performed sequentially by a supply vessel and viewed as a process evolving over time. Each voyage is characterized by voyage start time from the base (4pm), planned duration, voyage end time, and the sequence of installations to visit. The voyage have limits on minimum and maximum durations measured in days. The voyage start is defined as the start of vessel's unloading and loading operations at the base (8am). Vessel's turnaround time at the base is equal to 8 hours and coincides with the base's opening hours. After that, the vessel starts sailing towards the first installation on the voyage. Start of vessel's staying at installation begins upon vessel's arrival at installation. Installations are available for service during their opening hours. Opening hours for production platforms are between 7am and 7pm, while drilling rigs and other mobile offshore units are opened for service 24 hours a day. Duration of staying at installation is defined as the total time vessel spends at the installation before it starts sailing again. It includes waiting for the installation to be released by another vessel, waiting until opening hours at the installation, waiting for good weather to start vessel operations at installation, and service time (time needed to perform operations). Vessel's operations at the installation include discharge of deliveries from the vessel and collection of backloads from the installation. After completing operations at the installation, the vessel sails to the next installation on the voyage. After all installations are visited, the vessel sails back to the supply base. The voyage ends at the earliest start for unloading operations after return to the base.

2.2. *Weekly vessel schedule*

The weekly vessel schedule consists of a finite set of voyages. Each vessel in the weekly vessel schedule has its own weekly schedule describing a sequence of voyages to sail per week. The weekly schedule is built with respect to requirements from installations on weekly frequencies and spread of visits, deck and bulk cargo demands, installations opening hours and planned service times, locations of installations, speed and capacity of vessels, opening hours and capacity at the supply base. Weekly vessel schedule represents a solution to a fleet mix and periodic vehicle routing and scheduling problem studied in[4,5]. The exact solution method determining the minimal required number of vessels and the vessels weekly schedules is described in[4] consists of two stages. At first stage, for each of the available vessels the installations are clustered with respect to the vessel capacity and minimum and maximum number of installations on a voyage. As a voyage should last for more than one day and some installations are closed at night, the voyage with the shortest duration for each cluster is found by solving a multi-period travelling salesman problem with multiple time windows. At the second stage, the voyages with duration of two and three days are used as input to a set covering model assigning voyages to start days so that total vessel time-charter costs and the fuel costs are minimized with respect to the required installations' weekly visit frequency, spread of vessel departures to installations and the berth's capacity. This method can generate solutions only for relatively small instances. For larger instances, a large neighborhood search algorithm can be applied described in[5]. In practice, the weekly vessel schedules are constructed by the company's experts. An example of a weekly vessel schedule involving 4 vessels and 22 offshore installations is shown in Figure 1.

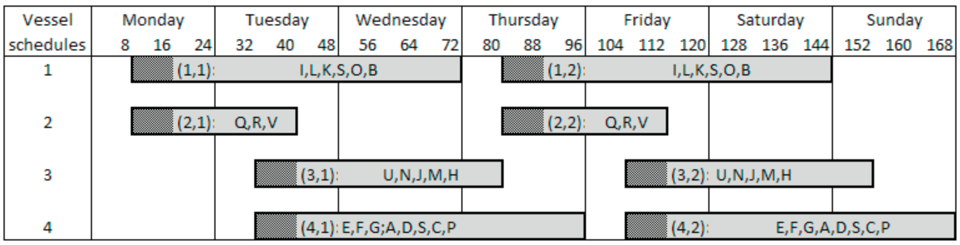

Fig. 1. Weekly sailing schedule.

The numbers in columns represent 8 hour time slots. The rectangular box encircled by a thick bold line represents a voyage. The dotted area depicts vessel's scheduled turnaround time at the supply base when loading and unloading operations take place. Each voyage is denoted by a pair (i, j), where i is a vessel schedule and j is the ordinal number of the voyage in this schedule. In the schedule in Figure 1 vessel 1 starts voyage (1,1) on Monday, and voyage (1,2) on Thursday. Vessel 2 starts voyages (2,1) and (2,2) on Monday and Thursday correspondingly. Vessel 3 starts voyage (3,1) on Tuesday and voyage (3,2) on Friday. Vessel 4 starts voyages (4,1) and (4,2) on Tuesday and Friday respectively.

There exist a precedence relationship between voyages in vessels' schedules. For example, in the weekly schedule for vessel 1 shown in Figure 1, voyage (1,1) is the predecessor of voyage (1,2), and voyage (1,2) is the successor of voyage (1,1). For simulation purposes, a weekly sailing schedule is transformed into a chronological sequence of voyage starts placed on the event calendar. The sequence of voyage starts for the weekly schedule illustrated in Figure 1 is shown in Figure 2. The arrors represent starts of voyages in the weekly schedule, while broken arrows point to the starts of the corresponding voyages-successors.

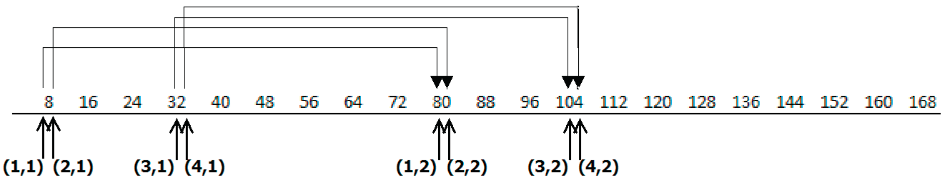

Fig. 2. Sequence of voyage starts for a weekly schedule.

2.3. Simulation model

The annual vessel schedule is generated from a set of consequtive weekly sailing schedules. We model the sequence of voyages in the annual vessel schedule as a system involving offshore installations, onshore supply base and the varying number of supply vessels. The system state is characterized by the number of vessels (time-charter and spot) being used offshore. Events occuring at discrete points in time and changing the state of the system are considered to be the fixed voyage start events and the generated voyage end events. By experimenting with various values for the design factor (number of time-charter vessels on long-term contract) and examining corresponding efficiency measure (annual vessel costs), the number of time-charter vessels minimizing annual vessel costs is determined. The total vessel costs are computed as the sum of the annual time-charter costs, the annual spot costs (based on the total number of spot days used) and the variable costs (total fuel costs).

The logic flowchart illustrating conceptual design of the developed simulation model is depicted in Figure 3. The model simulates voyages that are triggered by the corresponding voyage start events. An assignment of vessel to a voyage depends on the completion time of the predecessor of this voyage in the corresponding vessel schedule. If upon occurence of the vessel's voyage start event the vessel's preceeding voyage is completed, the vessel is assigned to this voyage. Otherwise, an available time-charter or spot vessel is assigned. The number of time-charter and spot vessels being used are updated at the voyage start event. The weather is modelled at least for the expected voyage

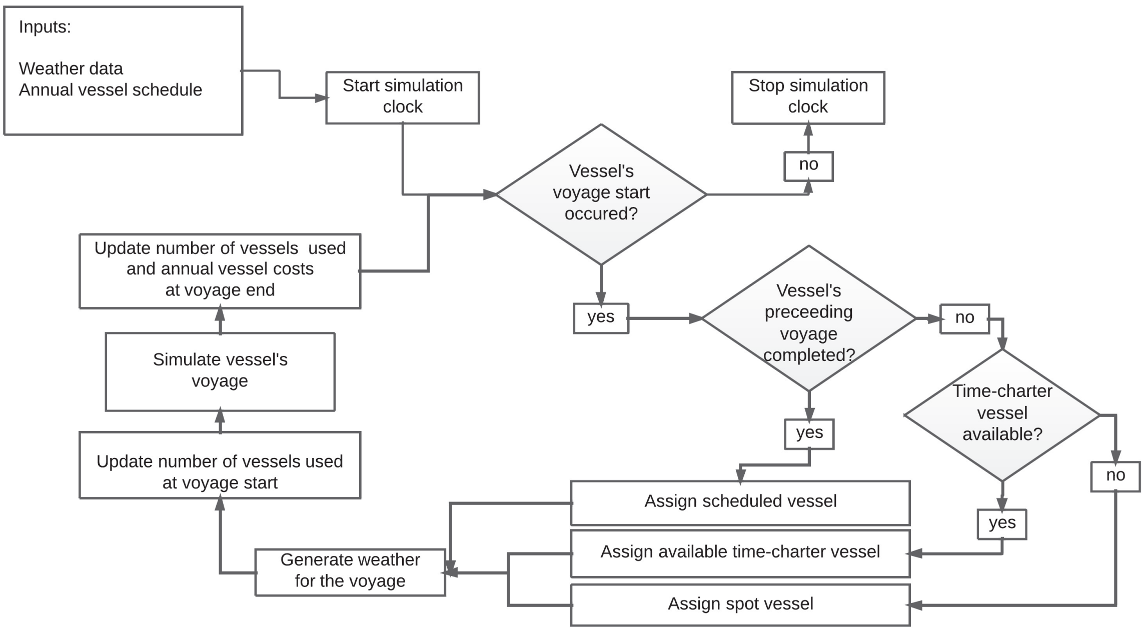

Fig. 3. Logic diagram of the discrete-event simulation model.

duration. The voyage is simulated and vessel's voyage end event is generated. The state variables and the performance measure are updated at the voyage end event. The simulation continues until all planned voyages are executed.

3. Operations durations

In this section we describe the ways to model the duration of service at installations and the sailing durations associated with voyage.

3.1. Service durations

Waiting for start of vessel operations at installations and service duration depend on uncertain weather conditions. Current safety norms require to cease vessel operations at installations when significant wave height (Hs), defined as the mean of the highest one third of the waves per observation period, exceeds 3.5 meters or when wind speed (Wsp) is above 40 knots [8]. The start of operations at installation depends on the duration of a weather window. It is defined as the time interval during which both Hs and Wsp do not exceed safety limits. The service at installation is allowed to be performed if and only if the length of the weather window at the start of operations is larger or equal to the weather-adjusted installation service time.

The service time at installation is quantified on the basis of installation's requirement for bulk and deck cargo to be discharged, backload and return waste to be collected. A common approach is to agree upon fixed duration of service time for each installation based on experience. The service duration at installation should account for weather margin (WM), i.e. an increase of service due to deteriorating weather conditions. The duration of service depends not only on start and the length of the weather window, but on conditions of the sea evaluated through Hs and Wsp statistical estimates.

In order to compute service duration at installation, the service time (ST) under normal weather conditions is split into an integer number of hours $\lfloor ST \rfloor$ and a fraction of an hour r. For each hour allocated for service the WM (in percentage) is defined according to Table 3.1 based on the value of either Hs or Wsp. It is assumed that the weather parameters are updated simultaneously every hour and remain constant until the next update. Column Hs shows the intervals for the significant wave height, column Wsp provides the corresponding ranges for wind speed. They are estimated based on experts opinions. The service duration (SD) is computed according to the following formula:

$$SD = \lfloor ST \rfloor + \left(\sum_{i=1}^{\lfloor ST \rfloor + 1} \frac{WM_i}{(1 + WM_i)} \right) \cdot (1 + WM_{i+1}), \tag{1}$$

where $\lfloor ST \rfloor$ is the number of one hour periods in the service time, WM_i is the weather margin for period i. $WM_i/(1 + WM_i)$ represents the percentage of hourly volume of work not finished within period i due to influence of deteriorated weather conditions, and $(WM_i/(1 + WM_i)) \cdot (1 + WM_{i+1})$ represents the time necessary to finish that work during the next period $i + 1$. If the second term in (1) exceeds 1 indicatinig that service will not be finished in period $i + 1$, service time ST is increased by one hour and second term is recomputed until it does not exceed 1. To account for the fractional remainder r, $WM_i/(1 + WM_i)$ is replaced with $WM_i/r(1 + WM_i)$ for $i = \lfloor ST \rfloor + 1$. In case the start of service occurs in a fractional hour (e.g, 03:45am or 3.75), 1 in the second term of (1) is replaced with the remainder of an hour (e.g., 0.25).

Table 1. Weather margin coefficients.

Hs [metres]	Wsp [knots]	WM [%]
[0 - 0.5]	4 - 6	0
(0.5 - 1]	7 - 10	0.1
(1 - 2]	11 - 16	0.15
(2 - 3]	17 - 21	0.2
(3 - 4]	22 - 27	0.3
(4 - 5.5]	28 - 33	0.5
(5.5 - 7.5]	34 - 40	0.8

Table 2. Aertssen coefficients according to [10].

		α	[0° – 30°)		[30° – 60°)		[60° – 150°)		[150° – 180°)	
BN	Hs[metres]	Wsp[knots]	m	n	m	n	m	n	m	n
5	2.5	17-21	900	2	700	2	350	1	100	0
6	4.0	22-27	1300	6	1000	5	500	3	200	1
7	5.5	28-33	2100	11	1400	8	700	5	400	2
8	7.5	34-40	3600	18	2300	12	1000	7	700	3

3.2. Sailing durations

The vessel's sailing time depends on stochastic weather conditions. To account for that, wave-dependent sailing time is introduced in the simulation model. Vessels operating on schedule often sail at designed speed and need to increase power margin up to 15 - 30% to compensate for rough sea conditions in contrast to calm waters operations. In our case, the sailing speed is reduced when weather conditions deteriorate.

The methods for estimation of vessel's speed reduction in the open sea due to waves and wind can be split into approximate and theoretical [10]. Approximate methods are accurate enough and easy to implement. They have an advantage of relying only on key vessel characteristics such as vessel's speed in calm waters, dead weight tonnage (DWT), vessel's length between perpendiculars. Two methods either best fitting the class of supply vessels (under 10,000 DWT) [11] or directly utilizing statistical estimates of the sea state conditions [12] are chosen. These methods are used to quantify vessel's speed reduction during sailing.

According to Aertssen formula [11] the speed reduction ΔV can be approximated as follows:

$$\frac{\Delta V}{V} \cdot 100\% = \frac{m}{L_{BP}} + n, \tag{2}$$

where V is vessel's design speed in knots in calm waters, L_{BP} is vessel's length between perpendiculars, m and n are empirical coefficients defined in Table 3.2. The columns of the table contain estimated values of m and n for waves hitting a vessel at a particular angle. The α is an angle off bow with respect to vessel's heading direction measured in degrees. The α parameter is derived by transformation of the mean wave direction (θ) estimate, defined as the mean of all the individual wave directions measured in degrees in a counterclockwise direction from the North Pole. The rows of the table contain estimates of m and n with respect to Beaufort wind force number (BN) [13] for a particular interval of α representing head sea, bow sea, bean sea and following sea. An advantage of that method is that it can be applied without consideration of the load of the vessel. The disdvantage of the approach is in exaggeration of the vessel's speed reduction ΔV due to linkage of m and n coefficients with Hs intervals rather than a precise estimate of Hs.

The more accurate approximate approach is to use Khokhlov formula from [12], which calculates speed reduction as follows:

$$V = V_0 - (0.745 \cdot H_s - 0.245 \cdot \alpha \cdot H_s) \cdot (1.0 - 1.35 \cdot 10^{-6} \cdot D \cdot V_0), \tag{3}$$

where V is wave-adjusted speed of a vessel in knots, V_0 is vessel's design speed in calm waters, α is angle of waves off-bow in radians, D represents vessel's deadweight (DWT) in tons and H_s is significant wave height. The method is applicable for any vessel with D varying between 4,000 and 20,000 DWT including supply vessels, and V_0 in the range between 9 and 20 knots. The standard error for the method does not exceed 0.5 knots. Since required vessel's characteritics as well as modelled estimates of H_s and α are available during simulation of voyage operations including sailing, this method was deployed as an alternative to the Aertssen method.

The duration of vessel's sailing on any leg between point of origin (base or installation) and point of destination (installation or base) is computed as follows. The distance of the leg is divided into the number of segments with length equal to the distance a vessel sails during an hour at design speed, and the remainder segment computed as the total leg distance minus sum of distances of segments. The total number of segments defines the number of iterations to perform in order to compute the total sailing duration on that leg. For each iteration, the weather parameters Hs and θ are computed with respect to vessel's current geographical position and current sailing time so that the weather-dependent speed reduction on that segment is computed according to method described above. Given the distance of the segment and the reduced sailing speed, actual sailing duration over that segment is computed. The total duration of the travel leg represents the sum of the durations of its segments. Values of H_s, θ estimates are retrieved from a set of corresponding univariate time series with respect to current sailing time. Linear interpolation method is used as the way of modeling weather conditions at a number of discrete points along each travel leg.

4. Input description and data modeling

The section contains description of experiments, general assumptions, modeling inputs such as weather data modeling and vessel charter rates modeling.

4.1. General assumptions and input data

The model was tested and validated on the real weekly vessel schedule depicted in Figure 1, where 8 voyages are scheduled to perform service for 22 installations. Inputs such as characteristics of the schedule and voyages, technical specifications of vessels, opening hours and geographical coordinates of offshore installations, and supply base are provided by the oil and gas company. Under assumption of ideal weather conditions the most cost-effective feasible fleet composition for this schedule consists of 4 time-charter vessels since the time-charter costs are much higher than the sailing costs. The possible increase in the number of vessels will result in the higher total costs since the total charter costs grow much faster than the sailing costs may decline due to shorter voyages.

The annual schedule has been simulated under uncertain weather conditions and forecasted spot vessels rates. The schedule assumes that all vessels are sailing at constant design speed of 12 knots. The model has been run under four levels of the experimental design factor (4, 5, 6, 7), using constant vessel speed and two vessel speed reduction approaches [11,12].

Vessel fuel consumption during sailing is approximated by a cubic function of the speed. Fuel consumption arising from vessel's activities at installations and at the supply base (such as waiting, maneuvering and unloading/loading) is modelled as well. Pairwise spherical sailing distances are derived using Haversine formula. The weather conditions influencing on sailing and service durations on each voyage are predicted for at least the expected duration of this voyage. Durations of sailing and staying periods at installations are computed by the simulation model dynamically.

The probability distribution functions are used to quantify values of random variables such as duration of vessel's maneuvering at installation, mobilization time of spot vessels. These random variables are modeled using triangular probability distribution *tria(min,mode,max)* best describing scarce number of interview-based estimates for these operations. Time to mobilize a spot vessel is measured in hours and modeled as $tria(4, 8, 12)$, while maneuvering at installation before start of the service is modelled as $tria(0.1, 0.4, 0.6)$.

Platform supply vessels are hired from the North Sea market on a long- and short-term basis. Daily time-charter and spot rates primarily depend on capacity of a vessel's deck area, which nowadays varies in the rage of [600,1200] m^2. The daily time-charter rate is determined as the average of long-term rates of platform supply vessels hired by the company, while daily spot rate depends on market conditions during the year. It is assumed that spot vessels are hired on daily basis to perform a single voyage. The spot vessels are demobilized (taken off-charter) when the voyage is completed.

4.2. Weather modeling

Modeling of statistical estimates of weather conditions is based on methods of time-series analysis applied to data provided by Norwegian Meteorological Institute (MET). It maintains a number of meteorological buoys along the Norwegian continental shelf, including the Norwegian part of the South-North Sea, however the number of buoyes is limited. Instead, the data is sampled from an operational spectral wave model with a lattice size of 10 kilometres (WAM10) that is currently used by MET for forecating and scientific research needs. From a two-dimensional waves spectra sea state parameters including Hs, Wsp and θ are computed. A number of time-series have been requested for the particular set of longtitude and latitude coordinates representing the location of the offshore installations as well as the offshore point near the shore as a reference point for the onshore supply base. Each time-series represents a data set with 157860 observations constituting 54 years of observations based on 3-hour period starting from January 1958 and until January 2011. The hind casted time-series sampled from WAM10 database have been validated by MET against data from 76 real buoys as described in[?] and conclusion was drawn that the data the modelled data is of hiqh quality and accuracy. A number of time-series has been reduced from 22 to 8 grid points due to preliminary clustering of installations. Due to model's lattice size several grid points are able to host more than one offshore installation reducing the amount of input weather data for the simulation model. The coordinates of the grid points coincide with selected installations and the offshore point.

The weather modeling approach is based on splitting each of the annual time-series into the number of blocks with equal amount of observations on monthly basis. The construction of time-series consists of random sampling a sequence of blocks from a predefined subset of all historical annual time-series. The 54 time-series used for generation of weather not only guarantees the sufficient number of possible weather paths, but allows to model the weather data as close as possible to the reality. The simulation of weather data is based on synchronous generation of time-series for three univariate sea state estimates as if it is measured in real conditions, namely significant waves height (Hs), mean waves direction (θ), and wind speed (Wsp). Simulated Hs, and Wsp form univariate time-series that are used by the model's logic to derive auxiliary time-series of alternating durations of two distinct weather states (high-state and low-state with respect to safety limit) for each sea state parameter used for generation of weather windows (characterized both by Hs and Wsp) affecting possibility and duration of service at installations. Generated Hs and θ time-series are used for computation of vessel's sailing durations as described in Section 3.2.

4.3. Spot vessel rates

The historical spot rates for different vessel categories are collected from a local shipbroker company in the form of time series from January 2008 to April 2012. They are reported according to vessel's size class, namely medium (e.g. 600 - 899 m^2) and large (e.g. 900+ m^2). The latter is the most-wanted by norwegian charterers and accordingly the most expensive. Time series are based on 2880 registered contracts for PSV vessels in the North Sea and consist of 52 weekly estimates per year per each category. The historical data for PSV600-899, PSV900+ categories is depicted in Figure 4a. The legend box includes notation for two supply vessel categories to distinguish spot rates between PSV600-899 and PSV900 class of vessel capacities, and notation for depicting total average spot rates for supply vessels. It shows significant fluctuations of the daily spot rate during 2008-2013 (between 50,000 and 350,000 NOK/day corresponding to approximately 6,000 and 42,000 EUR/day). Forecasting models and Monte Carlo simulation are applied in order to predict the likely development of daily spot rate for the year ahead. The obtained time-series of predicted forecast points is used as stochastic input within the simulation model.

Autoregressive integrated moving average (ARIMA) modeling is used to predict future values of the spot hire rate for PSV900+ category. Figure 4b illustrates the best fitting model $ARIMA\,(0,1,0)\,(0,1,0)$ [12]. Its mean forecast points (thick line) and corresponding prediction intervals are based on 1000 independent simulations. The y-axis display level of spot vessel rates in NOK, while the x-axis shows developemt of rates of the years. The legend box

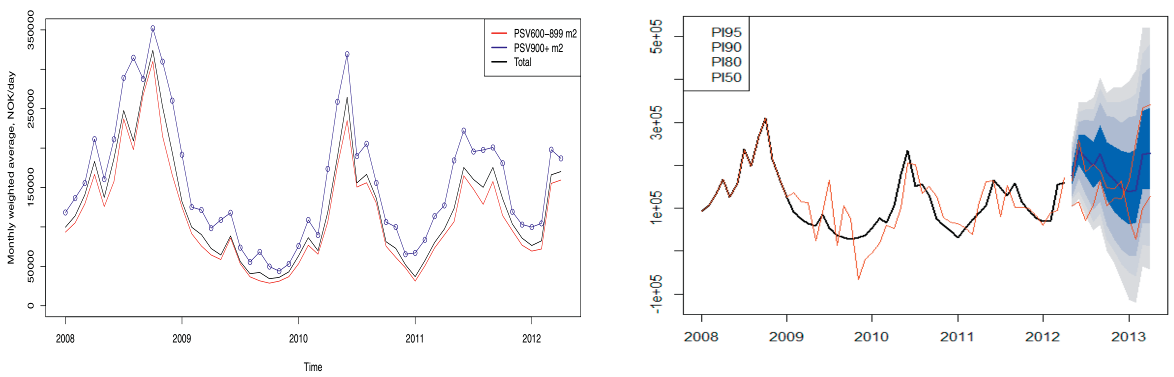

Fig. 4. Spot vessel rates: a) historical observations of PSV600-899, PSV900+ categories; b) best-fitting ARIMA model for PSV900+ category.

includes four prediction intervals at 95, 90 ,80, 50 levels illustrated in the form of gray regions imposed in decreasing order from the top to the centre of the plot. Two randomly simulated scenarios are plotted for illustrative purposes (thin lines) of the width of prediction intervals. The accuracy of the fit and produced forecast is estimated as moderate with mean absolute percentage error (MAPE) of 29.1%.

5. Output analysis

The model is implemented in Arena 13.0, the discrete-event simulation environment software from Rockwell Automation Technologies, Inc. To analyze the output results, the simulation model has been run for 100 replications, each of annual length. The sensitivity analysis of total annual vessel costs is performed by varying and examining the values for the chosen experimental design factor, namely the number of time-charter vessels on long-term contracts.

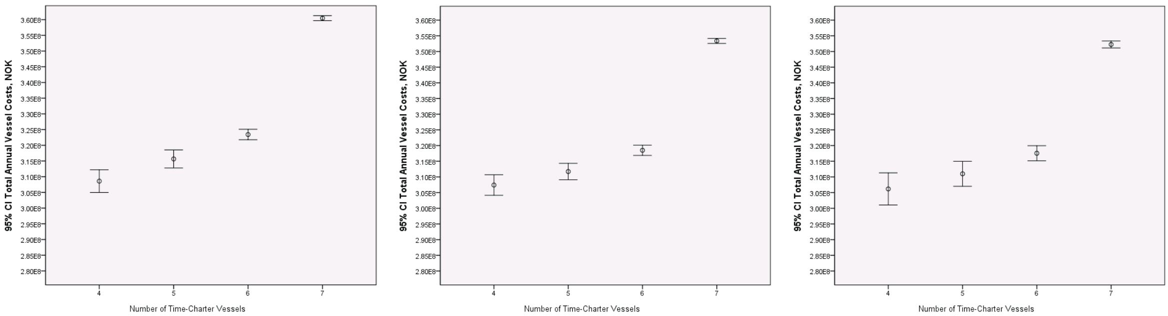

Fig. 5. 95% CI Total Annual Vessel Costs: a) without speed reduction (constant speed is maintained); b) with speed reduction by Aertssen); c) with speed reduction by Khokhlov.

The output plots have been constructed using PASW Statistics 18 software and illustrated in Figure 5. The y-axis denotes total annual vessel costs measured in Norwegian Kroner (NOK), the x-axis denotes tested values of the experimental design factor. Performed analysis of variance and results of one-way ANOVA test show that there is a statistically significant difference between the means of the total vessel costs for each tested number of time-charter vessels. However, the visual analysis of constructed error-bar plots indicate the similarity in behaviour of the total cost function. As expected, the simulation results show that the cost-optimal fleet size configuration independently of used vessel speed reduction approach is achieved by hiring 4 time-charter vessels. We recall that the tested annual vessel schedule requires at least four vessels to satisfy requirements from installations. Annual vessel costs grow approximately linearly with the increase in the number of time-charter vessels from 4 to 6. With the increase in the number of time-charter vessels the time-charter costs increase linearly, while the spot costs decrease. The rate of the time-charter costs increase is larger than the rate of the spot costs decrease. The slope of the total cost function is relatively small (about 2%) from 4 to 6 time-charter vessels. With the increase from 6 to 7 time-charter vessels the spot costs are equal to zero, thus the total cost function rapidly unlinearly grows (about 6 times faster).

The plotted results illustrate differences between different vessel's speed reduction methods. Khoklhov method (5c) yields the least total annual vessel costs, followed by Aertseen method (5b). The largest annual vessel costs are generated by the method assuming constant speed (5a).

6. Conclusions

Supply vessels are expensive and hired by oil and gas companies operating offshore. Determining the fleet size requires careful planning as supply vessel operations are complex, influenced by uncertain weather conditions, and affected by volatility in spot vessel rates. We present a discrete-event simulation model evaluating alternative fleet size configurations for supply time-charter vessels for an annual horizon. The contribution of this paper is in the development of original simulation model for determining the cost-efficient fleet size for annual supply vessel operations, and in the modeling of weather-dependent service durations and sailing durations. Collection and modeling of weather data required an effort. The model is validated and tested on real data. The output analysis shows that company's decision to hire four time-charter vessels on long-term contract is indeed the cost-efficient configuration. This study has received considerable attention of marine planners from the oil and gas company.

Acknowledgements

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